

Cooling Flows Induced by Compton Cooling due to Luminous Quasars in Clusters of Galaxies

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ABSTRACT

We have studied the effects of Compton cooling on cooling flow by performing numerical hydrodynamic calculations of the time evolution of hot gas in clusters of galaxies with luminous quasars. We assumed various temperatures for the hot intracluster gas. We have shown that the Compton cooling due to very luminous quasar is effective in inducing cooling flow, before radiative cooling flow is realized. The mass flux due to the cooling flow increases with time, as the Compton cooled region expands. However, the mass flux of the Compton cooling flow is not large, less than $1 M_{\odot} \text{ yr}^{-1}$ in our model, since Compton cooled region is limited in an inner galactic region around a quasar. Even though the quasar active phase ceased, the cooling flow will continue for at least 10^9 yr. The accreted mass is enough to explain X-ray absorption lines in high red shift quasars, if the Compton cooled gas is compressed by high pressure intracluster gas.

Key words: cooling flow: intracluster-medium: luminous quasar: hydrodynamics

1 INTRODUCTION

Radio-loud quasars have some characteristic features different from radio-quiet quasars. Radio-loud quasars are observed to be strong UV sources ($L_{\text{UV}} \sim 10^{46} - 10^{47} \text{ erg s}^{-1}$) (e.g., McDowell *et al.* 1989), and host galaxies of radio-loud quasars are found preferentially in high density environments (e.g., Smith and Heckman 1990) and are often central elliptical galaxies in clusters (Malkan 1984). Cooling flows sometimes appear around these quasars (Fabian 1994). For examples, Elvis *et al.* (1994) have shown strong X-ray absorption lines in high redshift quasars. They have suggested that the origin of absorbing gas is a cooling flow around quasar and have estimated that the column density of gas that absorbs the X-ray is up to 10^{23} cm^{-3} . Usually cooling flows in clusters of galaxies are proposed to be accretion flows of intracluster medium induced by radiative cooling (Sarazin 1986; Fabian *et al.* 1987; Forman 1988). Since radiative cooling time may be longer than the cosmic age at such a high z , another cooling process is needed for the cooling flow around quasar. Authors suggested that

cooling flows are induced by Compton cooling due to strong UV photons of quasars.

For the majority of quasars the bulk of the emitted electromagnetic luminosity is observed in the optical/UV/soft-X-ray spectral domain, the so-called big blue bump (Shields 1978; Malkan 1983). The origin of the big blue bump is accretion through a Keplerian disk or a non-Keplerian torus onto a supermassive black hole (Rees 1984). Fabian and Crawford (1992) (hereafter F.C.) have proposed that, since Compton scattering between strong UV photons and hot electrons can dominate cooling process for the hot gas in central region of a cluster, accretion by Compton cooling can supply the gas to a central massive black hole, and have shown that the accretion rate by Compton cooling flow can be larger than that of Bondi-accretion flow. We summarise this point according to F.C. as follows.

The Bondi accretion rate, \dot{M}_B , may be estimated as

$$\dot{M}_B = \frac{4\pi\alpha^2}{c_s^3} (GM)^2 \rho, \quad (1)$$

where ρ , c_s , M , α , are the gas density, sound speed, the central black hole mass and a factor depending on the adiabatic index of the gas, respectively. We estimate the typical value of \dot{M}_B in equation (1) as, $\dot{M}_B \sim 2.0 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$, where we take $\rho = 6 \times 10^{-26} \text{ g cm}^{-3}$, temperature $T = 10^7 \text{ K}$, $M = 10^9 M_{\odot}$ and $\alpha = 1$. At a radius R , the time-scale by Compton cooling, τ_c , is

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$$\tau_c \approx 10^{13} R_2^2 L_{47}^{-1} \text{ s}, \quad (2)$$

where the radius $R = 100 R_2$ pc and the luminosity $L = 10^{47} L_{47}$ erg s $^{-1}$. While the time-scale by bremsstrahlung cooling, τ_{rad} , is

$$\tau_{\text{rad}} \approx 6 \times 10^{13} T_7^{3/2} P_8^{-1} \text{ s}, \quad (3)$$

where the temperature $T = 10^7 T_7$ K and the pressure $P = nT = 10^8 P_8$ cm $^{-3}$ K. Therefore within a radius

$$R_c \approx 250 L_{47}^{1/2} T_7^{3/4} P_8^{-1/2} \text{ pc}, \quad (4)$$

Compton cooling dominates bremsstrahlung cooling in the highly ionized conditions, so that we can expect stable gas inflow since the cooling time does not depend on gas density. Consequently, all the gas at R_c flows into the central black hole, the accretion rate in this case is

$$\begin{aligned} \dot{M}_c &\approx \frac{4\pi R_c^3 \rho}{\tau_{\text{rad}}} \\ &\sim 1.45 L_{47}^{3/2} T_7^{1/4} \left(\frac{\rho}{6 \times 10^{-26} \text{ g cm}^{-3}} \right)^{1/2} M_\odot \text{ yr}^{-1} \end{aligned} \quad (5)$$

that is much larger than the Bondi accretion rate. The dependence of \dot{M}_c on L , i.e. $\dot{M}_c \propto L^{3/2}$ and the linear dependence of L on \dot{M} , means that, if $L > L_c$, the accretion induced by Compton cooling increases L further, where L_c is the quasar luminosity at the accretion rate of equation (5). On the other hand, if $L < L_c$ then \dot{M}_c is reduced and the luminosity continues to decline to L_B that is defined by the luminosity of a quasar at the mass accretion rate of \dot{M}_B .

When Compton cooling time is shorter than radiative cooling time in the inner central region, Compton cooling can induce the gas inflow before the radiation cooling induces the gas inflow. However, when the life time of quasar is comparable to Compton cooling time of the gas within R_c , gas flow can not be steady state during the duration time of the quasar. Therefore we should study numerically the time evolution of the gas inflow induced by Compton cooling. Moreover we expect another possibility that by the density concentration due to Compton cooling radiative cooling time would be shorter than Compton cooling time, so that the hot gas would be cool radiatively at the central region and that the density concentration could go on. We examine whether the mass accretion rate increases by the effect of Compton cooling and how Compton cooling affects the evolution of the intracluster gas by using hydrodynamic scheme. We fix the quasar luminosity in our model for simplicity through our all simulations.

In §2, we describe our model of the luminous quasar with the cooling flow in the central galaxy in a cluster. Our model incorporates the elliptical galaxy that includes stars, dark halos and cooling flow. In §3, we describe the results of our model calculations. In §4, we discuss the results and summarize our conclusions.

2 A MODEL FOR COOLING FLOW WITH LUMINOUS QUASAR IN A CENTRAL CLUSTER GALAXY

The central concept of our model is the evolution of density, temperature and accretion rate of the cooling flow in luminous elliptical host galaxy with a quasar. We assume that

the age of quasar is 10^8 yr. By treating the quasar as a source of UV photons, we consider Compton cooling process.

Since we concentrate on the evolution of the intracluster gas near the central galaxy, we calculate gas dynamics near the central galaxy. We assume that the cooling flow is spherically symmetric for simplicity.

2.1 Mass distribution of the stellar system and dark halo

The stars in the central galaxy are assumed to be distributed as the modified King profile with the density distribution given by

$$\rho_*(r) = \rho_c [1 + (r/r_c)^2]^{-3/2}, \quad (6)$$

where r is the radial distance and $r_c = 500$ pc is the core radius of the stellar distribution and $\rho_c = 3.0 \times 10^{-21}$ g cm $^{-3}$. Observations indicate that elliptical galaxies do not have flat cores, but rather cusp profiles (Hernquist 1990). However, the mass inside cusp is not so large, if we compare the mass within the core region. As we will show in Section 3, the cooling flow flux is mainly determined by the difference of pressures between at the inside and at the outside of the cooled region. Therefore, the choice of mass model with or without cusp is not so serious for our model.

We have assumed that the dark halo has a total mass which increases linearly with radial distance as suggested for early-type galaxies by X-ray mass determinations (e.g., Forman et al. 1985). The particular dark matter density distribution we have adopted is

$$\rho_d(r) = \rho_{dc} [1 + (r/r_d)^2]^{-1}, \quad (7)$$

where $r_d = 10$ kpc is the core radius of the dark halo distribution and $\rho_{dc} = 6.26 \times 10^{-25}$ g cm $^{-3}$.

The stellar and dark matter mass distributions, $M_*(r)$ and $M_D(r)$, can be determined by integrating the respective expressions for the densities. Carrying out the integrations, the mass distributions are found to be

$$M_*(r) = 4\pi \rho_c r_c^3 [\ln(x + \sqrt{x^2 + 1}) - x/\sqrt{x^2 + 1}] \quad (8)$$

and

$$M_D(r) = 4\pi \rho_{dc} r_d^3 (y - \tan^{-1} y), \quad (9)$$

where $x = r/r_c$ and $y = r/r_d$. The corresponding virial temperature of the model galaxy at r_c is 2×10^7 K.

We consider a supermassive black hole (hereafter SMBH) at the centre of galaxy. We assume that the mass of SMBH is $M_{\text{BH}} = 10^9 M_\odot$. The SMBH mass dominates within the radius

$$r_{\text{in}} = 172 \left(\frac{M_{\text{BH}}}{10^9 M_\odot} \right)^{1/3} \text{ pc.}$$

At such a radius the virial temperature T_{BH} due to the SMBH is

$$T_{\text{BH}} = 1.9 \times 10^6 \left(\frac{M_{\text{BH}}}{10^9 M_\odot} \right)^{2/3} \text{ K.}$$

2.2 The initial conditions

Given the mass distribution of the stars and dark matter, the initial density distribution of the hot gas can be derived

by assuming that it is in hydrostatic equilibrium. This assumption is valid when flow velocity is small. This condition can be written

$$\frac{dP(r)}{dr} = -\rho(r) \frac{GM(r)}{r^2}, \quad (10)$$

where $P(r)$ is the gas pressure, $\rho(r)$ is the gas density distribution, and G is the gravitational constant. The total mass $M(r)$ is given by

$$M(r) = M_*(r) + M_D(r) + M_{\text{BH}}. \quad (11)$$

The gas density distribution for an isothermal temperature is given by

$$\rho(r) = \rho_{g0} \exp[-(\phi(r) - \phi(0)) \frac{\mu m_H}{kT_0}], \quad (12)$$

where k is the Boltzmann constant, T_0 is the initial isothermal temperature, and $\phi(r)$ is the gravitational potential by the stellar and dark matter mass distributions. We take $\rho_{g0} = 6 \times 10^{-26}$ g cm⁻³, which maybe a typical value of interstellar matter in the host galaxy. We assume various value of T_0 as shown in Table 1, since we want to study Compton cooling effects on intracluster gas in various types of cluster of galaxies. We redefine R_c by using equation (2) and $\tau_c = 10^8$ yr. By the new definition, we get $R_c = 540$ pc for $L_{\text{UV}} = 10^{46}$ erg s⁻¹ and $R_c = 1700$ pc for $L_{\text{UV}} = 10^{47}$ erg s⁻¹.

Since we assume that flow velocity is small except for the vicinity of a SMBH, the initial velocity distribution in the central region is given by

$$v(r) = -\frac{n_e(r) n_i(r) \Lambda_0 T_0^\alpha r^2}{\rho(r) G M(r)}, \quad (13)$$

where $n_e(r)$ is the electron density, $n_i(r)$ is the ion density, $\Lambda_0 T_0^\alpha$ is the emissivity. We use the steady state energy equation. In the outer region, the velocity distribution is given by

$$v(r) = -\frac{r_{\text{inner}}^2 \rho(r_{\text{inner}}) v(r_{\text{inner}})}{r^2 \rho(r)}. \quad (14)$$

We assume that r_{inner} is r_d .

We assume that cooling function $\Lambda(T) = \Lambda_0 T^\alpha$. We take $\Lambda(T)$ to be that given by Raymond, Cox and Smith (1976) for an optically thin, fully ionized gas with the cosmic abundance for $T \geq 10^4$ K and zero for $T < 10^4$ K. $\Lambda(T)$ is given cgs unit by

$$\Lambda(T) = \begin{cases} 2.2 \times 10^{-27} T^{0.5}, & \text{for } T > 4 \times 10^7 \\ 5.3 \times 10^{-17} T^{-0.87}, & \text{for } 4 \times 10^7 > T > 2 \times 10^6 \\ 6.2 \times 10^{-19} T^{-0.6}, & \text{for } 2 \times 10^6 > T > 10^5 \\ 1.0 \times 10^{-24} T^{0.55}, & \text{for } 10^5 > T > 10^4. \end{cases} \quad (15)$$

2.3 The basic equations

We calculate the time evolution of spherically symmetric X-ray emitting hot gas models. We assume that the gas is ideal. The hydrodynamic equations for a hot gas are

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \rho v) = 0, \quad (16)$$

$$\frac{\partial \rho v}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \rho v^2) = -\frac{\partial P}{\partial r} - \rho \frac{GM}{r^2}, \quad (17)$$

$$\frac{\partial U}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \{r^2 (U+P)v\} = -\rho v \frac{GM}{r^2} - n_e n_i \Lambda_0 T^\alpha - \frac{\rho \Lambda_c(T)}{r^2}, \quad (18)$$

where

$$P = \frac{\rho k T}{\mu m_H} \quad (19)$$

is the gas pressure and

$$U = \frac{1}{2} \rho v^2 + \frac{P}{\gamma - 1} \quad (20)$$

is the sum of kinetic energy and thermal energy per unit volume, and

$$\Lambda_c(T) = \Lambda_{c0} L T \quad (21)$$

is the coefficient related with the Compton cooling and L is the UV luminosity of the quasar. Λ_{c0} is the constant,

$$\Lambda_{c0} = \frac{1.1 \sigma_T k}{2.1 \mu m_e c^2}, \quad (22)$$

where σ_T is the cross section for the Thomson scattering. We take the $\gamma = 5/3$. Other physical variables have usual meanings.

2.4 Timescale

We have performed numerical calculations in the variety of cases. In Table ??, we show the numerical model parameters and Bondi accretion rate \dot{M}_b to compare with our numerical results. We take $\alpha = 1$ and $\tau_c = 10^8$ yr. In Fig. 1, we show the cooling time (τ_c and τ_{rad}) in the variety of temperature and luminosity. It is interesting that Compton cooling time depends on the radius and luminosity and does not depend on the gas density and temperature.

2.5 The simulation

We assume six cases of temperature of intracluster medium. Instead of the gravitational confinement of the hot intracluster gas in the cluster of galaxies, we assume the outer boundary confines this hot gas. We use the flux-split scheme with second-order accuracy in space and the first-order accuracy in time (van Leer 1982, van Albada, van Leer and Roberts 1982). This scheme is the one of the upwind scheme for the Euler equation. We calculate the region from $r = 50$ pc to 50 kpc. The calculated region covers the black hole mass dominated region as shown in Section 2.1. We use a mesh with 4996 elements.

We take the boundary conditions as follows. At the inner and outer boundaries, the spatial gradient of the velocity is zero. At the inner boundaries, we assume that gas mass flux and total energy flux are same those in the cell next to the inner boundary. By this inner boundary condition, we obtain smooth accretion flow. At the outer boundaries, the density and energy are fixed in time.

We have calculated the evolution of the cooling flow for the both cases of the existence of Compton cooling and no Compton cooling (only radiative cooling) for $t = 1 \times 10^9$ yr from the initial situation.

3 NUMERICAL RESULTS

We have shown that Compton cooling is dominant cooling process within R_c which is defined by equation (4) and that

there is the region where Compton cooling time is shorter than the age of a quasar as shown in Fig. 1. In this region, we can expect a cooling flow induced by Compton cooling within the lifetime of a quasar. From our numerical results, we found that Compton cooling induces a cooling flow, even if the temperature of intracluster gas is as high as 10^8 K. However, the mass flux is smaller than that estimated by equation (5), since the lifetime of a quasar is too short to develop the cooling flow structure. We found the case in which the cooling flow induced by Compton cooling continues after the lifetime of quasar in the lower temperature intracluster gas case.

In Fig. 2, we show the results of 7.d747 model as the strong Compton cooling flow case. These figures show the evolution of the density, the velocity, the temperature and the accretion rate of the gas in 7.d747 model. In this model, we assume the luminous quasar with $L_{\text{UV}} = 10^{47}$ erg s $^{-1}$ and the temperature of intracluster gas, 7×10^7 K. In this case, since Compton cooling is very effective, the gas in the inner region of galaxy cools by Compton cooling within the lifetime of a quasar and the cooled gas inflow is realized as shown in Fig. 2(b). We should note that radiative cooling time of the hot gas initially filled in the host galaxy is longer than the calculation time and we do not find any cooling flow in 7.d7rad model in which we do not consider Compton cooling. The inflow velocity attains 40 km s $^{-1}$ at r_c at 10^8 yr. The mass flux is as large as $0.45 M_\odot$ yr $^{-1}$ in this stage. This is smaller than that estimated by equation (5). After the lifetime of a quasar, we stop Compton cooling, that is, we calculate the energy equation without Compton cooling. After then, the cooled gas flows into the central region, and the hot gas occupies the whole region. Finally, the cooling flow disappears.

Next, we show the weak Compton-cooling-flow case in Fig. 3. In Fig. 3, we show 7.d746 model. Fig. 3 shows that the temperature of gas within 500 pc decreases due to Compton cooling. As a result, the gas density increases by the compression due to the high pressure of the outer hot gas. However, the flow velocity and the mass flux are very small in the inner region, as shown in Fig. 3(b) and Fig. 3(d). The hot gas in the inner region is in nearly hydrostatic equilibrium. The small mass flux would not affect the evolution of a quasar and the host galaxy. Since the gas cooled by Compton cooling is not thermally unstable as shown by equation (2) and the gas temperature in this region remains rather high temperature in comparison with the virial temperature of the host galaxy, the cooling flow is not realized. This is the reason why gas is nearly hydrostatic state.

Next, we show the Compton-cooling-induced-cooling flow case in Fig. 4. Fig. 4 shows the numerical results of 5d747 model and that the gas in the inner region rapidly cools by Compton cooling, and attains less than 10^7 K within 10^8 yr in the central region of the host galaxy. In this case, if we do not consider Compton cooling, radiative cooling flow does not appear as shown in Fig. 5. Since the temperature of gas near r_c becomes much less than the virial temperature of the host galaxy, 2×10^7 K, the gas inflow is induced and the mass flux attains to $0.4 M_\odot$ yr $^{-1}$. After 10^8 yr $^{-1}$, we stop Compton cooling, and the inflow velocity decreases. However, radiative cooling flow continues to 10^9 yr. The mass flux is $0.2 M_\odot$ yr $^{-1}$ at 10^9 yr. We can conclude that the cooling flow after the lifetime of a quasar in

5d747 model is initially induced by Compton cooling and is maintained by radiative cooling.

Next, We show the numerical results of 5d746 model in Fig. 6. In 5d746 model, we assume one-tenth of a quasar luminosity of 5d747 model, 10^{46} erg s $^{-1}$. In this case, the gas in the inner region of the host galaxy cools by Compton cooling and the density in the cooled gas region increases. However, the accretion rate is as small as $0.01 M_\odot$ yr $^{-1}$, since the Compton cooling rate is smaller than 5d747 model. After Compton cooling stopped, the gas density and temperature return to the initial state. Although the gas cools by Compton cooling, the cooling flow disappears after Compton cooling stops. From these results, we can interpret that the strong Compton cooling induces radiative cooling flow in 5d747 model.

4 DISCUSSION

We have shown that, if a quasar has very strong UV source ($L_{\text{UV}} \geq 10^{47}$ erg s $^{-1}$), the cooling flow can be induced by the quasar during the quasar active phase. In this case, intracluster gas is accumulated into the host galaxy. The total mass accreted into the host galaxy is not so large but enough mass to maintain the activity of an active galactic nuclei. On the other hand, for the typical lifetime of a quasar, 10^8 yr, a quasar activity ceases before Compton cooling becomes effective to induce cooling flow for the high temperature intracluster gas case (e.g., initial gas temperature of $\sim 10^8$ K), if a quasar does not have a strong UV source ($L_{\text{UV}} \leq 10^{46}$ erg s $^{-1}$).

Due to Compton cooling, the gas temperature decreases, and the gas density increases by the compression of high pressure of outer gas. The gas flows in this stage corresponds to the pressure driven accretion (Sarazin 1986). If the temperature of cooled gas becomes lower than the virial temperature of the host galaxy, the inflow induced by Compton cooling occurs. As shown in Table 2, the mass flux at 10^8 yr can be approximated by using the equation (5), except for replacement of τ_{rad} by 10^8 yr and R_c by the distance where Compton cooling time equals to 10^8 yr. Then, equation (5) should be changed as $\dot{M}_c \sim 0.5 L_{47}^{3/2}$. It is possible, that the feedback on central accretion due to the increased quasar luminosity, as Compton cooling become effective, would increase the mass flow from large radii to large enough values to account for central accretion rate, if the quasar UV luminosity reaches 10^{48} erg s $^{-1}$.

Compton cooling affects the halo gas in the host galaxy and increases its gas density. As a result, after a quasar activity ceases and Compton cooling become ineffective, there are the cases that radiative cooling flow continues, although the mass flux is smaller.

Compton cooling is not thermally unstable, since Compton cooling does not depend on the gas density. Although Compton cooling time is much smaller than the simulation time, we have gotten the results that the temperature of hot gas does not attain very low temperature in the inner region in the high temperature case. The reason is as follows: In 7d746 model, the flow time at 10^8 yr is $\sim 10^7$ yr at 100 pc, since $v \sim 10$ km s $^{-1}$. There is not enough time to cool further for Compton cooled gas in the calculated region, since Compton cooling time in this region is as large as

10^7 yr. On the other hand, in 5d747 model, the flow time at 10^8 yr is as large as 4×10^7 yr at $r \sim 1000$ pc, since $v \sim 25$ km s $^{-1}$. Since Compton cooling time is as large as 10^7 yr at $r \sim 1000$ pc, Compton cooling is effective to reduce the temperature of intracluster gas.

Elvis *et al.* (1994) showed the evidence of X-ray absorption in high redshift quasars. They found that these quasars are very luminous X-ray sources up to 10^{48} erg s $^{-1}$. They suggested that a cooling flow around the quasar accounts for the X-ray absorption. If these quasars have comparable magnitude of UV flux with X-ray, Compton cooling would be very effective in these quasars. As discussed above, since $\dot{M}_c \propto L_{UV}^{3/2}$, the mass accretion rate becomes large. This cooled gas in Compton cooling flow would correspond to X-ray absorption. We compare column density of our Compton cooling flow models with the column density observed in the high redshift quasars. As shown in Section 3, the gas density distribution may be approximated by $\rho = \rho_0(r/r_0)^{-1}$, where $\rho_0 \sim 2 \times 10^{-25}$ g cm $^{-3}$ and $r_0 \sim 1000$ pc. The column density N is estimated as

$$N = 10^{21} \left(\frac{\rho_0}{2 \times 10^{-25} \text{ g cm}^{-3}} \right) \left(\frac{r_0}{1 \text{ kpc}} \right) \ln \frac{(r_{\max}/1 \text{ kpc})}{(r_{\text{in}}/1 \text{ pc})} \text{ cm}^{-3}.$$

This column density is smaller than the observed value. The compression of cooled gas is expected, since the pressure of central gas is very high. It is possible to explain the high column density at quasar observed in high redshift by Compton cooling flow by this compression.

In our numerical results, the cooled gas flows through the inner boundary. It is not clear that how the gas accretes onto the central black hole or an accretion disk around the SMBH. Then we hold our model luminosity fixed. The cooling of inflow from large radii to accretion at small radii is beyond the scope of our model. A particular question is whether the increase in the virial temperature inside 100 pc due to the presence of a SMBH leads to efficient infall to smallse radii or not.

We conclude that a cooling flow can be induced by Compton cooling in the UV luminous quasar case, since in the clustering scenario of formation of cosmic structure quasars are expected to be formed in highly dense massive self-gravitating gas clouds (Katz *et al.* 1994).

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Figure 1. the Compton cooling time for $L_{\text{UV}} = 10^{46} \text{ erg s}^{-1}$ and $L_{\text{UV}} = 10^{47} \text{ erg s}^{-1}$ and the radiative cooling time for initial gas with various temperature; Initial gas distribution is given by equation (12).

Figure 2. Evolution for model 7.d747. (a), (b), (c) and (d) are the results of distribution of density, velocity, temperature and accretion rate, respectively. In (a), the density distribution becomes more steep with time. In the central region, the density increases from $6 \times 10^{-26} \text{ g cm}^{-3}$ to $5 \times 10^{-24} \text{ g cm}^{-3}$. Since the gas concentrates, the hot gas flows inward from the outer region. As shown in (c), in the central region, the temperature decreases from $3 \times 10^7 \text{ K}$ to $1 \times 10^6 \text{ K}$ by Compton cooling. Then the flow velocity increases to $2.4 \times 10^7 \text{ cm s}^{-1}$ and the accretion rate also increases to $0.4 M_{\odot} \text{ yr}^{-1}$ in the central region. The gas temperature declines gradually, but when the radiative cooling time becomes shorter than the Compton cooling time, the gas temperature declines rapidly. From 10^8 yr to 10^9 yr , the gas flow changes into the quasi- hydrostatic state.

Figure 3. The same as Fig. 2 , but for model 7.d746 As shown in (a) and (c), at 10^8 yr the density increases and the temperature decreases, but the profiles are not more rapid than those in Fig. 2(a) and (c). From 10^8 yr to 10^9 yr , the gas state returns to the initial hydrostatic state. For this case, the gas temperature is about $2 \times 10^7 \text{ K}$ at R_c .

Figure 4. The same as Fig. 2, but for model 5.d747.

Figure 5. The same as Fig. 2, but for model 5.d7rad.

Figure 6. The same as Fig. 2, but for model 5.d746.





















